AD-750 340

MOMENTUM TRANSFER FROM EXPLOSION-DRIVEN SHOCK WAVES TO TREE STEMS

M. P. Keown, et al

Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

1972

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

207

AD 750 340

AD750340

MOMENTUM TRANSFER FROM EXPLOSION-DRIVEN SHOCK WAVES TO TREE STEMS

DDC
NOV 7 1972

M. P. KEOWN, H. NIKODEM, J. K. STOLL
U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI

PART I: INTRODUCTION

An important characteristic of the U. S. Army's tactical mobility is the widespread and effective use of troop-carrying helicopters. The enemy's intensive utilization of forest cover for sanctuaries and approach and retreat routes requires that the Army conduct operations in forest environments. Helicopter landing zones (HLZ's) are essential in such operations for tactical deployment of troops, resupply, evacuation of wounded, etc. The enemy's ingenious use of various antihelicopter mines and boobytraps makes the use of existing clearings for HLZ's dangerous; further, establishing an HLZ in hostile territory by conventional engineering techniques is both hazardous and time-consuming. A recent study(1) and experience in South Vietnam have shown that single explosive charges can be used to clear vegetation from areas large enough for HLZ's.

The successful and efficient utilization of bombs for clearing HLZ's can be greatly enhanced by the use of techniques for predicting the dimensions of clearings that can be obtained with various bomb yields in various kinds of forests.

The output of an analytical solution that is to be useful in comparing explosive clearing devices during the design stage or in evaluating the effectiveness of a given device in a given forest environment must include tree remnant height with respect to horizontal distance from the explosion center. Stated more briefly, clearing geometry is an essential product of an analytical solution if it is to prove useful in operational planning. Analytical techniques for predicting tree stem failure as a function of wood strength properties, stem diameter, and shock wave (front) characteristics are presented in this paper. Also discussed is the application of this analytical capability for estimation of clearing geometry and comparison with vertical ground clearances required for HLZ's.

Copies 175

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

distribution is unlimited

PART II: TREE STEM FAILURE

The failure curvature of a tree stem under dynamic loading can be derived by treating the tree as a vertical cylindrical wood beam. The bending moment at any cross section of a beam is expressed in equation form as:

$$M_b = \frac{\sigma \cdot I}{r} \tag{1}$$

where

M_b = static bending moment

σ = maximum stress occurring at a section

I = $\pi r^4/4$ = moment of inertia of circular cross section of a beam with respect to the neutral axis

r = radius of beam (distance from the neutral axis to the outermost fiber)

Substituting the modulus of rupture, S, for maximum stress[2] in equation 1 yields:

$$M_c = \frac{S \cdot I}{r} \tag{2}$$

where M_c = bending moment required for failure.

A mathematical description of stem curvature in response to impulse loading is a prerequisite to analysis of stem failure curvature. The bending moment at any height above the ground and at any time is described by the following equation:

$$EI(x) \left[\frac{\partial^2 y(x,t)}{\partial x^2}\right] = M_b(x,t) \tag{3}$$

where

E = Young's modulus parallel to longitudinal axis of beam

$\frac{\partial^2 y}{\partial x^2}$ = geometric curvature of the beam

$y(x,t)$ = deflection perpendicular to longitudinal axis of beam

x = linear distance along beam

t = time after initial application of driving force

By introducing equation 2 into equation 3 and rearranging terms, the equation for beam (stem) failure curvature K_c is:

$$K_c = \frac{S}{Er} \tag{4}$$

Whenever the value for the term $\partial^2 y/\partial x^2 \geq K_c$, stem failure will occur for given values of S, E, and r. Failure was assumed to

occur before momentum transferred to the stem through the crown could contribute significantly to the failure. Equation 4 is valid for any x and t and does not specify a unique height on the stem.

To determine curvature as a function of height on the beam (stem) and time, the following equation was written:(1)

$$\frac{\partial mv(x,t)}{\partial t} + \frac{\partial^2}{\partial x^2} EI(x) \left[\frac{\partial^2 y(x,t)}{\partial x^2}\right] = F(x,t) \tag{5}$$

where

$m = \rho A$ = mass per unit length of cylinder, where ρ = density of wood beam and A = cross sectional area of the beam

$v = \frac{\partial y(x,t)}{\partial t}$ = velocity perpendicular to the longitudinal axis of the beam

$F(x,t)$ = external loading force per unit length of the beam as a function of time and height on the beam

The first term of equation 5 represents the inertia force per unit length of an elemental mass (i.e. the mass associated with a unit length) and to accelerate the mass in a horizontal direction y for a given unit t. The second derivative of the bending moment (equation 3) with respect to linear distance along the beam is internal load intensity in force per unit length. In the static condition, the sum of the internal and external load intensities is zero, i.e. F = 0. The system is in equilibrium because there are no unbalanced forces. Any excess in the external load intensity over the internal load intensity must be balanced by inertial forces that produce acceleration and bending of the beam.

If I, ρ, and E in equation 5 are assumed to be constants and the cross-sectional area of the beam πr^2, the following working form of equation 5 is generated:

$$\rho \pi r^2 \frac{\partial v(x,t)}{\partial t} + EI(x) \frac{\partial^4 y(x,t)}{\partial x^4} = F(x,t) \tag{6}$$

PART III: LOADING FUNCTION

To arrive at a solution of equation 6, a mathematical definition of the loading function F(x,t) was established in terms of total effective pressure impulse J_t. J_t can be equated to dynamic pressure impulse J if appropriate tree parameters are considered; namely, the stem radius and characteristic drag coefficient. Values of J are known or can be accurately estimated for various weapon yields. The loading function had to account for the fact that J decreases approximately with the square of the distance from the

explosion center EC. Also to be accounted for was the resolution of J to obtain the horizontal component as a function of height on the stem.

The loading function (fig. 1) was characterized as follows: Between $t \leqq 0$ and $t = T_r$ (pulse rise time), $F(x,t)$ increases as a function of the stem loading area; between $t = T_r$ and $t \geqq T_p$ (positive pulse duration), $F(x,t)$ decays linearly to zero. $F(x,t)$ has to be a pulse of finite duration in time.

In addition, two assumptions were made:

a. The initial contact of the shock front with a tree stem occurs at a height equal to that of the EC.

b. The shock front shape is a circular arc and is neither attenuated nor distorted by encounters with tree stems.

Based on the above considerations and assumptions, the following expressions were written to describe the loading function:[1]

$$F(x,t)_{rise} = \frac{4rJ_{tR}R^2\cos\phi}{T_pL^2}\left(1-\frac{t-T_r}{T_p-T_r}\right)\left[1-\left(1-\frac{t}{T_r}\right)^2\right]^{1/2} \quad \ldots \text{ for } 0 \leq t \leq T_r\,,$$

$$F(x,t)_{decay} = \frac{4rJ_{tR}R^2\cos\phi}{T_pL^2}\left(1-\frac{t-T_r}{T_p-T_r}\right) \quad \ldots \text{ for } T_r \leq t \leq T_p \qquad (7)$$

where

R = horizontal distance from EC to tree
L = radial distance from EC to point of interest on tree
ϕ = the vertical angle formed by a line through EC and L and the vertical direction

A value for J_t was calculated by the following equation:

$$J_t = JC_d + P_r\left(\frac{2r}{U}\right) \qquad (8)$$

where

C_d = drag coefficient of stem
U = shock front velocity
P_r = reflected pressure (later discussed)

PART IV: EXPRESSION OF THE BEAM (STEM) MOTION EQUATION IN FINITE DIFFERENCE FORM

The fourth order differential equation describing the dynamic deformation of an elastic cylindrical beam (equation 6) is

2ll

difficult to solve in closed form for an arbitrary function, $F(x,t)$. Therefore, a numerical scheme was necessary to obtain a solution of equation 6. The derivations were represented in finite difference form as follows:[3]

$$\rho\pi r^2 \left(\frac{Y_{i-1,j}-2Y_{i,j}+Y_{i+1,j}}{\Delta t^2}\right) + \frac{E\pi^4}{4}\left(\frac{Y_{i,j-2}-4Y_{i,j-1}+6Y_{i,j}-4Y_{i,j+1}+Y_{i,j+2}}{\Delta H^4}\right)$$

$$= F_{i,j}$$

where

$Y_{i,j}$ = horizontal displacement at time step i and nodal point j above the ground
Δt = time increment
ΔH = distance increment along the beam
i = time subscript
j = distance subscript
$F_{i,j}$ = forcing function in terms of discrete values ($F(x,t)$ implies a continuous function)

The stem model is illustrated in fig. 2. The stem was assumed to be hinged at its base, so that it could rotate but not translate at its point of attachment, and only in the vertical plane passing through the longitudinal axis of the stem and the EC.

To obtain unique solutions of equation 6, boundary conditions must be specified. Since equation 6 describes the motion of a stem whose characteristics are stated above, the required conditions can be defined as (a) at $x = 0$, $y = 0$; (b) the bending moment at $x = 0$ (base of stem) is zero at all times; (c) the bending moment at $x = h$ (top of stem) is zero at all times; and (d) the shear at $x = h$ is zero at all times. These conditions can be expressed mathematically as follows:

$$\text{At } x = 0,\ y(o,t) = 0, \text{ and } EI(x)\,\frac{\partial^2 y(o,t)}{\partial x^2} = 0$$

$$\text{At } x = h,\ EI(x)\,\frac{\partial^2 y(h,t)}{\partial x^2} = 0, \text{ and } EI(x)\,\frac{\partial^3 y(h,t)}{\partial x^3} = 0$$

Expressions of the boundary conditions in finite difference form are:

$$\text{At } x = 0 \text{ (base of stem)},\ Y_{i,j} = 0 \text{ and } \frac{Y_{i,j-1}-2Y_{i,j}+Y_{i,j+1}}{\Delta H^2} = 0$$

$$\text{At } x = h \text{ (top of stem)},\ \frac{Y_{i,j-1}-2Y_{i,j}+Y_{i,j+1}}{\Delta H^2} = 0 \text{ and}$$

$$\frac{-Y_{i,j-2}+2Y_{i,j-1}-2Y_{i,j+2}+Y_{i,j+2}}{2\Delta H^3} = 0$$

The initial value problem relevant to time is solved by considering that the displacement and velocity at $t \leq 0$ are zero. These conditions are expressed as: $Y(x,o) = 0$ and $\partial Y(x,o)/\partial t = 0$. At $t = 0$ the initial conditions can be expressed in finite difference form by

$$Y_{i,j} = 0, \text{ and } \frac{-Y_{i-1,j}+Y_{i+1,j}}{2\Delta t} = 0$$

PART V: SOLUTION OF FINITE DIFFERENCE EQUATION FOR A REFERENCE CASE

The solution of the finite difference equation (mathematical model) for a particular set of parameter values (i.e. dynamic pressure impulse, wood density, stem radius, etc.) is discussed in the following paragraphs. Hereafter, this is referred to as the "reference case solution." By appropriately scaling the parameters (discussed later in the text), solving a specific problem (i.e. a problem involving any possible set of parameter values) becomes relatively easy. Specific case parameter values are simply scaled such that the results of the reference case solution are applicable; the complex computational procedures involved in a complete solution for each case are avoided.

For the reference case, values for the tree parameters were selected within the ranges expected to occur in nature. Model parameters were considered to be of two general types--variable and fixed. Variable parameters are those for which changes in values can be used (either directly or by scaling) in solving a specific problem. Fixed parameters are assigned roles as integral parts of the model. Once values for these parameters are selected, they are treated as being invariant.

Variable parameters are tabulated below with the corresponding values used in the reference case solution.

Parameter	Values*
Total effective pressure impulse	4.99×10^6 dyne-msec/cm^2**
Diameter of stem	6, 8, 12, 20, 40, 60, and 75 cm

*Since changes in variable parameter values can be used in solving a specific problem, the values listed have little significance, other than they are not unrealistic, and warrant no discussion.
**A value of 0.75 was used for the drag coefficient in computing J_t.

Parameter (Con.)	Values (Con.)
Density of wood	0.8 g/cm^3
Modulus of rupture	7.19×10^9 $dynes/cm^2$
Young's modulus parallel to longitudinal axis	1.20×10^{11} $dynes/cm^2$

The fixed parameter values selected are as follows.

Parameter	Values
Height of EC	3 m
Radius of shock front	10 m
Velocity of shock front	10^3 m/sec
Duration of positive pulse	10 msec
Height of stem	20 m

Before the above values for fixed parameters were selected, the effect of varying each of them on maximum stem curvature was studied prior to selecting the final values. On the basis of a 20-cm-diam tree stem, the parameter of interest was varied while all other parameters were held equal to those listed for the variable parameters.

The finite difference method was used to solve equation 6 on a G-440 computer. For a given stem radius, computations of stem deflection and first, second (stem curvature), third, and fourth derivatives of the deflection were made by 25-cm increments of stem height and 0.1 msec intervals of time after initial contact of the shock front. The output included values of the derivatives by 25-cm increments for the full 20-m stem height and 1-msec time intervals. For each stem diameter studied, the value of maximum stem curvature times stem radius Kr and height on the stem at which it occurred were then tabulated by time in order of increasing time after shock-front contact. The results of the reference case solution are summarized in fig. 3. Time increases to the right on the curve for a given stem radius, and each increase in maximum stem curvature corresponds with a successively higher position on the stem.

PART VI: EXPERIMENTAL DATA ON LOADING FUNCTION

A limited number of field experiments were performed[3] to obtain final average velocity measurements of logs (stem segments) thrown into free flight by blast forces. Data were obtained for 13 logs of either 10- or 20-cm diameter ranging in mass from 9054 to 36,083 grams. Log motion data were obtained with time-displacement gages, velocity gages, accelerometers, and high-speed photography. The logs were positioned at varying distances from the EC within a range of peak overpressures of 20 to 200 psi.

Predicted and measured final average velocities are compared in fig. 4. An approximated linear relation indicates the measured velocities to be somewhat higher than the predicted ones. The data could be adjusted for a match, however, if a higher value were used for the drag coefficient, i.e. >0.75, in the prediction equation. This is further suggested by the position of the smooth-log data point. The outer surface of this log had been turned down in a lathe.

The equation used to predict final velocities for the logs used in the experiment was derived from the loading function in the following manner.

The momentum transferred from the shock front to the stem and the loading function are related as follows:

$$M = \int_0^{T_p} F(x,t)dt$$

Integrating equation 7 as indicated shows that momentum transfer per unit length is:

$$M = 2rJ_t \tag{9}$$

Substituting equation 8 into equation 9 yields:

$$M = 2r\left[JC_d + P_r\ \left(\frac{2r}{U}\right)\right] \tag{10}$$

JC_d is generated by the air drag on the stem within the shock front. The second momentum component is due to a pressure differential generated between the side facing the incident shock front and the lee side of the tree stem. The term 2r/U is the shock-front transit time across the stem. The last term of equation 10 can be expressed in terms of the reference dynamic pressure impulse as:

$$P_r\ \left(\frac{2r}{U}\right) = 0.5\ J_b\ \left(\frac{r}{10}\right) \tag{11}$$

For a stem radius of 10 cm, the term P_r (2r/U) was calculated with available overpressure values for a selected reference case J_b.[4] The results indicated that for a given distance, the calculated value was equal to approximately one-half the corresponding dynamic pressure impulse. To satisfy any stem diameter, both sides of equation 11 were multiplied by the term r/10.

According to cube-root scaling laws,[5] the following relation is valid for any explosion:

$$J = J_b\ \left(\frac{W}{W_b}\right)^{1/3} \tag{12}$$

215

where

W = weapon yield in equivalent weight of TNT

W_b = weapon yield for selected reference case

Substituting equations 11 and 12 into equation 10 and stem diameter d for 2r yields:

$$M = d \cdot J \left[C_d + \frac{1}{40 \left(\frac{W}{W_b}\right)^{1/3}} \right] \quad (13)$$

The total momentum transfer per unit length of stem can be expressed in terms of velocity change as:

$$M = \frac{m}{\ell} \quad (V_f - V_i) \quad (14)$$

where

m = mass of log

ℓ = length of log

V_f = final velocity at the end of the momentum transfer

V_i = initial velocity at the beginning of the momentum transfer

The initial velocity is zero since the log is at rest when initial contact is made by the shock front. By equating equations 13 and 14 and solving for V_f, the final expression becomes:

$$V_f = J \left(C_d + \frac{d}{40 \left(\frac{W}{W_b}\right)^{1/3}} \right) \frac{d\ell}{m}$$

PART VII: SCALING SPECIFIC CASE VALUES TO REFERENCE CASE CONDITIONS

Equation 6 can, for practical purposes, be solved directly only with the aid of an electronic computer. Either directly or with appropriate scaling, however, equation 4 can be used to account for differences in values of some of the parameters in equation 6. This advantageous approach was followed; it provides a means by which maximum curvature-height on stem relations from the reference case can be used in a desk solution of blast-tree interaction in a specific case.

For practical application, the modulus of rupture and Young's modulus must be treated as constants for a given tree species. For simplification only, terms were rearranged in equation 4 so that $K_c \cdot r = S/E$. The failure criterion S/E is, of course, also constant for a given tree species. The U. S. Department of Agriculture Wood Handbook No. 72 is one source of tree strength properties. This handbook contains values for Young's modulus and rupture modulus for 101 tree species that can be used to calculate failure curvature for any stem size.

To predict tree remnant height for any specific case, values for S, E, and ρ (obtained from the Wood Handbook) are substituted into the equation on the ordinate of graph 4 fig. 5 to obtain a value for failure curvature K_c. K_c is then scaled to the reference case and associated with a scaled value of r to obtain $K_{co} \cdot r_o$. Because the curves in graph 4 represent maximum curvature of a stem at a given time, entry of a value for $K_{co} \cdot r_o$ on the y-axis, by definition, makes that value for $K \cdot r$ equivalent to failure curvature. It follows, therefore, that the corresponding value on the x-axis is equivalent to tree remnant height.

Since equation 6 is linear with respect to deflection, stem curvature and, therefore, maximum curvature will change proportionally with changes in driving force on transferred momentum, i.e.

$$\frac{K}{K_o} = \frac{F}{F_o} = \frac{M}{M_o}$$

The subscript "o" indicates a specific case value scaled to match reference case results.

A specific case of maximum curvature times stem radius can, therefore, be defined in terms of the reference case:

$$K \cdot r = \left(\frac{M}{M_o}\right) K_o \cdot r$$

and in turn, be equated to the stem failure criterion:

$$\frac{M}{M_o} (K_{co} \cdot r) = \frac{S}{E}$$

References 1 and 5 show that by using terms from momentum transfer equations and scaling functions related to weapon yield and mechanical and physical properties of a tree stem, the following equation can be derived:

$$K_{co} \cdot r = \left(\frac{1}{J_b \left(\frac{W}{W_b}\right)^{1/3}}\right)\left(\frac{SJ_{to}\rho}{E\rho_o}\right)\left(\frac{1}{0.75 + \frac{d}{40 \left(\frac{W}{W_b}\right)^{1/3}}}\right) \tag{15}$$

Reference 1 also shows

$$r_o = r \left(\frac{E}{E_o}\right)^{1/2} \left(\frac{\rho_o}{\rho}\right)^{1/2} \tag{16}$$

The nomograph in fig. 5 was constructed to provide a graphic solution for predicting tree remnant height. Essentially, it is a graphic representation of the scaling procedures described in equations 15 and 16. An abbreviated step-by-step method for predicting remnant tree heights for any specific problem is included with the nomograph. Use of the nomograph is not recommended for situations in which EC is >5m above the ground surface.

PART VIII: COMPUTER SOLUTION OF NOMOGRAPH

The nomograph in fig. 5 was programmed for a G-440 computer operating in the time-sharing mode. After verification of the computer code and a plotting routine, helicopter data files were added to permit output of graphs like that shown in fig. 6. The computer code was used to predict remnant tree height versus distance from ground zero (vegetation profile) for a given weapon yield, stem diameter, and wood strength class. Six wood strength classes were selected for ranges of values determined for a modification of the stem failure criterion, i.e. $S\rho/E$. The predicted vegetation profile resulting from blast damage and the vertical clearance requirements for a HLZ are compared in fig. 6. The vegetation profile can be compared to any combination of helicopter departure angle and touch zone radius. Curves similar to the one shown in fig. 6 are available for seven stem diameter values that represent the upper limits of seven stem diameter class ranges. The seven classes include a total range in stem diameter values from 0 to 91 cm. A set of seven curves is produced for all six wood strength classes (42 curves total) for a given weapon yield. By the use of transparent overlay templates showing landing zone geometry profiles to the same scale, the adequacy of clearings for use as HLZ's can be estimated. Estimates of the size and shape of clearings tend to be conservative for forests with low-crown conditions.

Remnant tree heights also were predicted for 230 individual trees surveyed at an experimental site in Fort Benning, Georgia.(1) An M121 general purpose bomb was emplaced in a tripod frame with the lower tip about 1 m above the ground surface. Following detonation of the weapon, remnant heights were measured for the trees surveyed before the blast. A probability distribution of the ratio of maximum remnant height (MRH) to predicted remnant height (PRH) is given in fig. 6. The scale on the ordinate axis indicates the proportion of "times" the ratio will be exceeded. The probability for a ratio of 1.0 is approximately 0.11, which means that for the experimental conditions, only 11 percent of the remnant tree heights exceeded the predicted values, i.e. the prediction reliability was 89 percent. By using the data in figs. 6 and 7, the probability that remnant heights will exceed required takeoff clearances as shown in fig. 6, for any distance from ground zero can be determined. This is accomplished by selecting a distance value on the abscissa in fig. 6 and reading the corresponding height values on the ordinate axis for both curves: Substitute for PRH in the ratio (fig. 7) the height value read for the vegetation profile and for MRH the height value of vertical clearance. The resulting value calculated for the MRH/PRH ratio is entered on the abscissa of fig. 7 and projected vertically to the curve and horizontally to intersect the ordinate axis. The value intersected on the ordinate axis is the probability, which can be expressed as a percent, that the predicted remnant height will exceed the takeoff clearances. If the average number of trees per unit area is known, the probability values can be used to obtain an

estimate of the number of trees that must be removed after a detonation. A simplified graphic solution for use in making such estimates is available.

SUMMARY

The data shown indicate that solution of a mathematical representation of momentum transfer from a shock front to a tree stem closely approximates values measured during 13 field experiments. These results provide a preliminary verification of the theoretical driving force term in the equation describing beam (stem) motion under impulse loading.

The finite difference technique was used to numerically solve the stem motion equation for a particular set of parameter values (reference case solution) as a function of height on the stem and time. The results were used to obtain relationships of maximum stem curvature and height on the stem for seven stem diameter sizes ranging from 6 to 75 cm. By appropriate scaling of blast and tree parameters, stem failure criterion was related to maximum stem curvature for the reference case solution.

Predicted and measured tree remnant heights were compared for 230 trees surveyed before and after detonation of an M121 bomb (3.6 metric ton yield) at Fort Benning, Georgia. The predictive reliability for the 230 trees was 89 percent.

The success of the tree remnant height prediction methods suggest that the size and shape of clearings constructed instantly with large munitions can be estimated reliably in evaluating sites for HLZ's.

REFERENCES

1. Benn, B. O., et al, "Evaluation of Construction Munitions for Clearing Helicopter Landing Zones in Forested Areas, Project Combat Trap (U)," Report 1, "Effects of Bomb Blast on Trees (U)," (CONFIDENTIAL), Aug 69, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

2. Timoshenko, S. and MacCullough, G. H., Elements of Strength of Materials, 3rd ed., Van Nostrand, Princeton, N. J., 1949, pp 122 and 123.

3. Stoll, J. K. and M. P. Keown, "Experimental Data on Momentum Transfer from an Explosion to a Tree Stem," U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss. (publication pending).

4. Kingery, C. N., "Tree Blowdown from Air Blast," (CONFIDENTIAL), Aug 68, Ballistic Research Laboratories, Aberdeen Proving Ground, Md.

5. Hq, DA, "The Effects of Nuclear Weapons," Pamphlet No. 39-3, Apr 62 (revised and reprinted Feb 64), Washington, D. C.

219

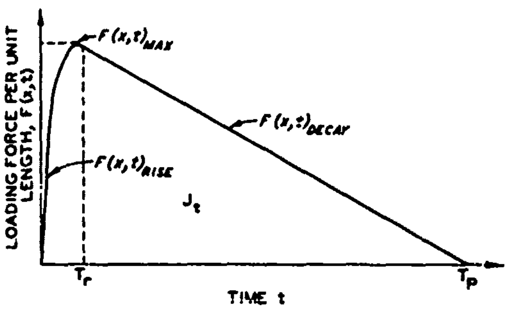


Fig. 1. Rise and Decay Components of Loading Function

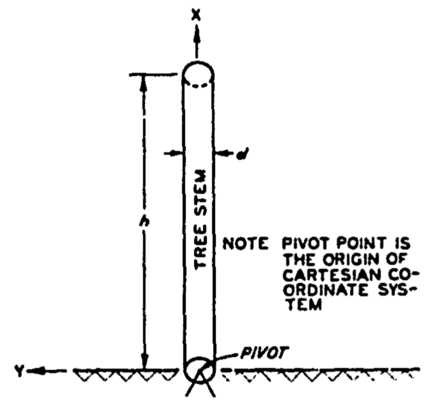


Fig. 2. Stem Model

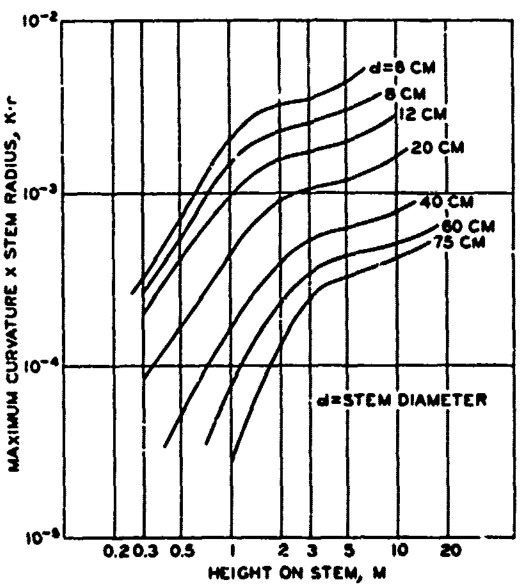


Fig. 3. Maximum Curvature Times Stem Radius as Related to Height of Occurrence on Stem

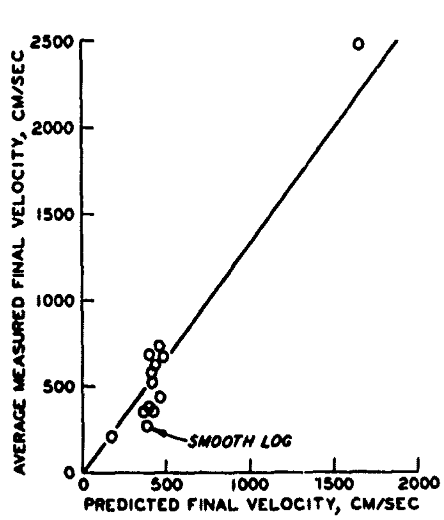
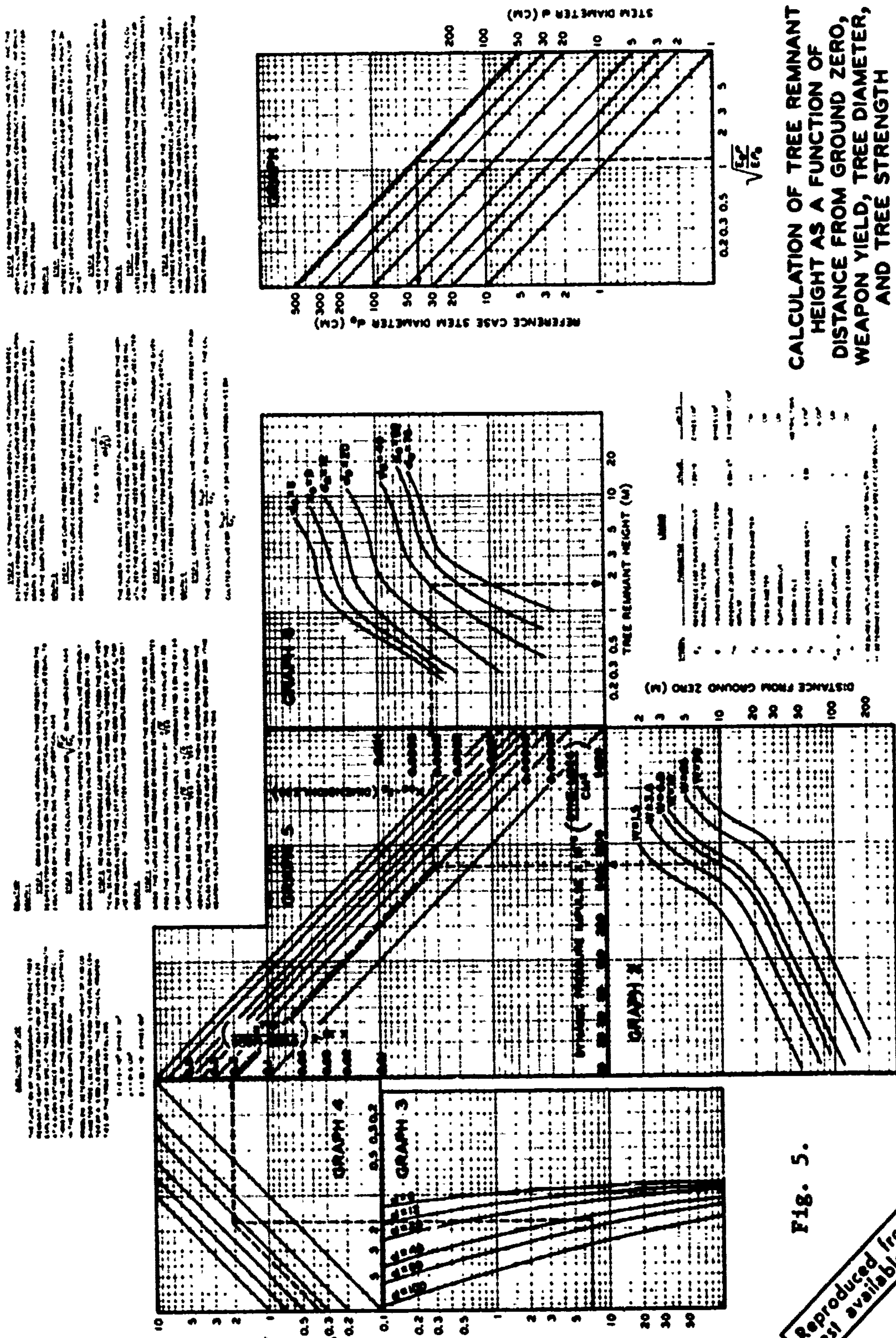


Fig. 4.

Comparison of Predicted and Measured Final Velocities for Logs

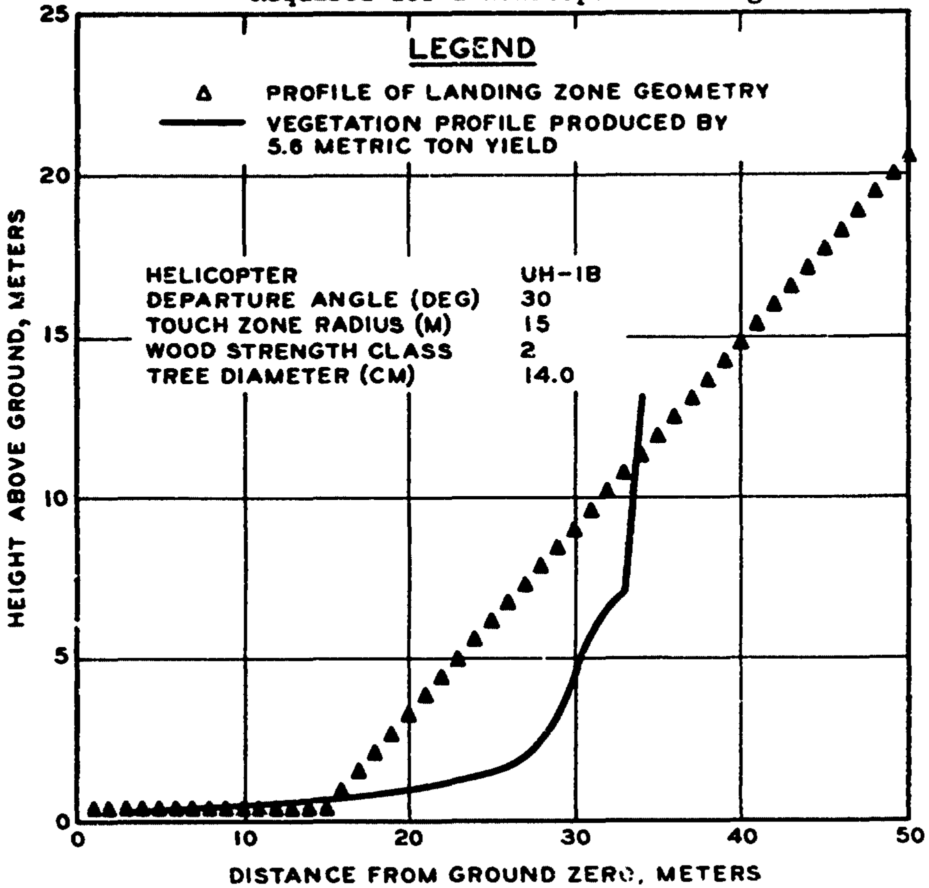


CALCULATION OF TREE REMNANT HEIGHT AS A FUNCTION OF DISTANCE FROM GROUND ZERO, WEAPON YIELD, TREE DIAMETER, AND TREE STRENGTH

Fig. 5.

Reproduced from best available copy.

Fig. 6. Comparison of Height Profile for Damaged Vegetation and Vertical Ground Clearances Required for a Helicopter Landing Zone



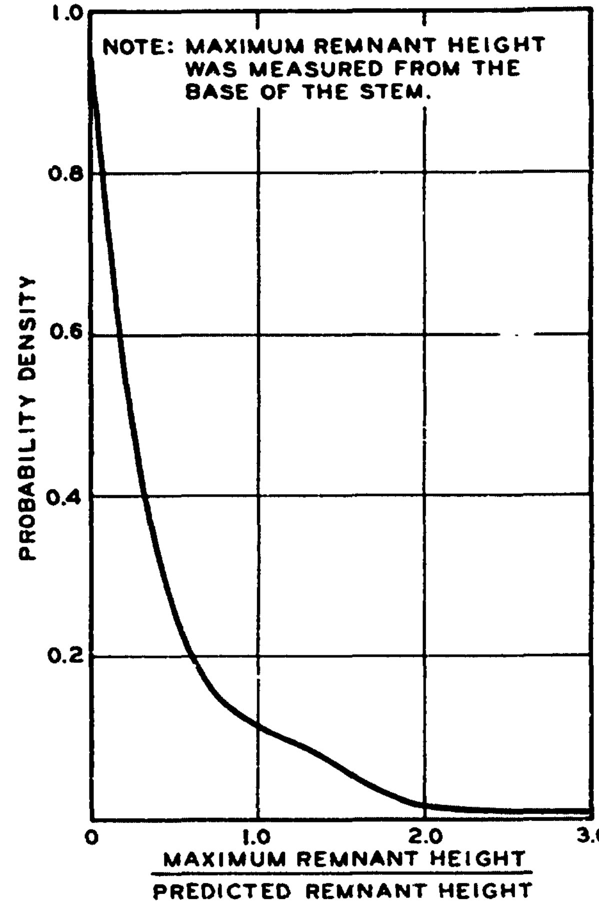


Fig. 7. Probability Distribution of the Ratio of Maximum Remnant Height to Predicted Remnant Height

189 END